AD-771 385

# ADAPTIVE AMTI RADAR


Lawrence E. Brennan, et al

Technology Service Corporation



Prepared for:

Naval Air Systems Command

19 October 1973

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

UNCLASSIFIED
Security Classification

AD 771385

# DOCUMENT CONTROL DATA - R & D

*(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)*

| | |
|---|---|
| 1. ORIGINATING ACTIVITY (Corporate author) Technology Service Corporation | 2a. REPORT SECURITY CLASSIFICATION Unclassified |
| | 2b. GROUP N/A |

3. REPORT TITLE

ADAPTIVE AMTI RADAR

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report 1 July 1973 to 30 September 1973

5. AUTHOR(S) (First name, middle initial, last name)

Lawrence E. Brennan and John D. Mallett

| | | |
|---|---|---|
| 6. REPORT DATE 19 October 1973 | 7a. TOTAL NO. OF PAGES 24 | 7b. NO. OF REFS 6 |

| | |
|---|---|
| 8a. CONTRACT OR GRANT NO. N00019-73-C-0093 | 9a. ORIGINATOR'S REPORT NUMBER(S) TSC-PD-096-4 |
| b. PROJECT NO. | |
| c. | 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) None |
| d. | |

10. DISTRIBUTION STATEMENT

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

| | |
|---|---|
| 11. SUPPLEMENTARY NOTES | 12. SPONSORING MILITARY ACTIVITY Department of the Navy Naval Air Systems Command Washington, D.C. |

13. ABSTRACT


Adaptive signal processing in airborne radars with array antennas can provide a high level of MTI performance, including automatic platform motion compensation. Methods of simplifying adaptive AMTI radars by forming subarray outputs and adding these subarray outputs adaptively are described and evaluated in this report. It is shown that in radars with many-element arrays, e.g., AI radars, ground AMTI performance can be achieved in systems with roughly nine subarray outputs from the antenna. The results obtained during the preceding three quarters of the study are summarized in this final report, and relate to the performance of space-time adaptive radar in non-uniform clutter, conformal array antennas in adaptive AMTI radar, and a method of achieving rapid convergence in adaptive systems.




DD FORM 1 NOV 65 1473

UNCLASSIFIED
Security Classification

UNCLASSIFIED

Security Classification

| 14. KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Adaptive Array Antennas | | | | | | |
| Adaptive Radar | | | | | | |
| AMTI (airborne moving target indication) | | | | | | |

UNCLASSIFIED

Security Classification

**Technology Service Corporation**

225 Santa Monica Blvd.
Santa Monica, Calif. 90401

# ADAPTIVE AMTI RADAR

TSC-PD-096-4

by

J. D. Mallett
L. E. Brennan

19 October 1973

FINAL REPORT

SUBMITTED TO: The Naval Air Systems Command
on Contract N00019-73-C-0093

## TABLE OF CONTENTS

## 1.0 INTRODUCTION

This final report on a study of adaptive signal processing in airborne MTI radars presents the results obtained during the fourth and final quarter of the contract. Results for the earlier nine months of the study are detailed in quarterly progress reports and are reviewed briefly in Section 2 below. This study was concerned primarily with AMTI radars which are controlled adaptively in both space and time, i.e., both the array antenna pattern and the MTI filter response are controlled adaptively. These adaptive systems provide automatic platform motion compensation by changing the array illumination function from pulse to pulse. Both jamming and clutter are rejected simulataneously in these systems, which also compensate for aircraft structure in the antenna near field.

Under earlier NASC contracts, TSC has performed a series of studies of space-time adaptive radar in AEW systems. These earlier studies assumed a linear array antenna containing approximately 10 elements. During the study reported here, this investigation was extended to AI type radars where the array antenna contains a much larger number of elements. One method of simplifying an adaptive AI radar is to form a small number of sub-array outputs from the array, and combine these sub-array outputs with adaptively controlled weights. This subject is discussed in Section 3 of this final report. It is shown that subarray systems of this type with approximately nine antenna outputs and 18 adaptive degrees of freedom can provide good AMTI performance over a range of scan angles and radar platform velocities.

Different methods of subarraying to obtain the adaptive system inputs are compared.

The conclusions reached during this study are contained in Section 4.

## 2.0 REVIEW OF QUARTERLY REPORTS

The first quarterly report[1] discussed the performance of space-time adaptive AMTI radar in systems with curved antennas. Conformal arrays, flush mounted on the surface of an aircraft have important aerodynamic advantages (no protruding radomes, such as rotodomes) and electronic advantages (larger apertures, reduced effects of radome reflection and refraction). Adaptive AMTI radar with a parabolic array antenna, representative of the nose of an interceptor, was investigated. It was shown that the space-time adaptive technique provides excellent AMTI performance in these systems, both for a scan angle along the radar platform ground track and for electronic scan 30° off the ground track. With a 2 pulse, 20 array element system, MTI gains in excess of 90 dB are theoretically achievable when the pulse-element weights are optimized. It was also shown that the performance of these systems, both with parabolic and with linear arrays, is seriously degraded when the array element spacing is one wavelength or greater.

Two topics are included in the second quarterly report[2]: the effect of a non-uniform clutter distribution on space-time adaptive radar, and the sample covariance matrix technique for speeding convergence in all adaptive array systems. With regard to the first topic, adaptive radar systems were evaluated for cases where the angular distribution of clutter backscatter ($\sigma_o$) varies with range. Optimum weights were computed for one non-uniform angular clutter distribution and these weights were tested against a second

angular distribution. It was found that, in some cases, the weights optimized for distribution 1 provide significantly less MTI gain against distribution 2. However, when the covariance matrix is averaged over both distributions of clutter (i.e., over the entire range search interval), weights based on this average covariance matrix generally perform well against both of the individual clutter distributions.

The convergence rate of adaptive arrays employing the conventional Applebaum or Widrow control loops has been found to be very slow in many cases of interest. This problem occurs in space-time adaptive AMTI radar in particular. The convergence rate of the adaptive weights to near-optimum values can be increased by changing the control loop parameters, but this results in an increase in control loop noise. For many clutter distributions and array geometries, it is not possible to select control loop parameters which provide good performance, i.e., adequate convergence rate to follow antenna scan and low control loop noise. A method of achieving rapid convergence in all cases is described in the second quarterly report. It is shown that a sample covariance matrix based on a relatively small number of data samples can be used to compute a set of near-optimum adaptive weights. An expression is derived for the probability distribution of the signal-to-noise ratio when adaptive weights are based on this sample covariance matrix algorithm. The detailed derivation of the equations for this distribution are contained in the third quarterly report[3].

With this method of generating adaptive weights, a signal-to-noise ratio approximately 3dB below the optimum is achieved when the number of samples contained in the sample covariance matrix is twice the number of adaptive degrees of freedom. For example, a space-time adaptive system based on 3 pulses and 10 elements would require only 60 data samples. In a pulsed radar, one data sample of the clutter-plus-noise environment is obtained in a time interval of one pulse length (or reciprocal bandwidth in systems with pulse compression). With a one microsecond pulse length, an adequate estimate of the covariance matrix can be obtained in 60 microseconds. In space-time adaptive systems, data for the corresponding range interval must be available also for the preceding pulse. Using this algorithm, a more than adequate convergence rate can be obtained in all adaptive radar configurations and clutter/noise distributions. This theory was verified by simulation of a 2 pulse, 4 element system. Results are shown in Table 1 for a case in which the conventional adaptive loops converged very slowly. As shown in the third column, only 38 dB of a possible 62.2 dB MTI gain was achieved by the adaptive array using the conventional control loops. Both the theory and simulation show that the sample covariance matrix technique provides 58 dB of MTI gain when only 20 samples of the noise field are used.

Table 1. Comparison of Convergence in Adaptive Loops and Sample Covariance Matrix (SMI) Systems

| 4 Elements 2 Pulses (N=2x4) Spacing = .5λ<br>Interpulse Motion = .2 λ/pulse Steady-State Gain = 62.2 dB<br>MTI GAIN (dB) | | | |
|---|---|---|---|
| No. of Samples (K) | SMI Theory* | SMI Simulation | Adaptive Loops |
| 10 | | 55.6 | 15.5 |
| 15 | 57.14 | 58.9 | 15.8 |
| 20 | 58.97 | 58.6 | 17 |
| 800 | | | 37 |
| 2000 | | | 38 |

*Values given by $62.2 - 10 \log_{10}\left(\frac{K-N+2}{K+1}\right)$.

## 3.0 SUBARRAYING IN ADAPTIVE AI RADAR

The detection of low flying aircraft with AI radars requires a high level of MTI performance. This is particularly true over land because of the large clutter backscattering from terrain in the radar beam. Adaptive AMTI radar, with varying antenna patterns from pulse to pulse, can provide excellent MTI performance when fully adaptive array antennas are employed. In a fully adaptive system, the output of each array element is weighted separately before formation of the receiving beam. This requires a separate adaptive control loop for each element or formation of a very large covariance matrix. For example, an X-band radar with a 2 ft x 2 ft antenna contains approximately 1600 half-wavelength spaced elements. A fully adaptive system generating 1600 element weights on two or more consecutive pulses is clearly not practical in the next decade or so.

One method of simplifying these systems is to form a smaller set of separate antenna outputs, e.g. from subarrays, and to add these outputs with adaptively controlled weights. Several different methods of subarraying have been investigated and MTI performance calculated for these simpler systems as a function of scan angle and radar platform velocity.

The method of adaptive AMTI processing considered in these studies is shown in Figure 1. A coherent pulsed radar was assumed, with a uniformly illuminated transmit antenna. In practice, an AI radar at X or C band would employ a two-dimensional array antenna. A linear array was considered in these analyses with adaptivity in azimuth only. A system of this type could be implemented with a planar array antenna by combining the outputs

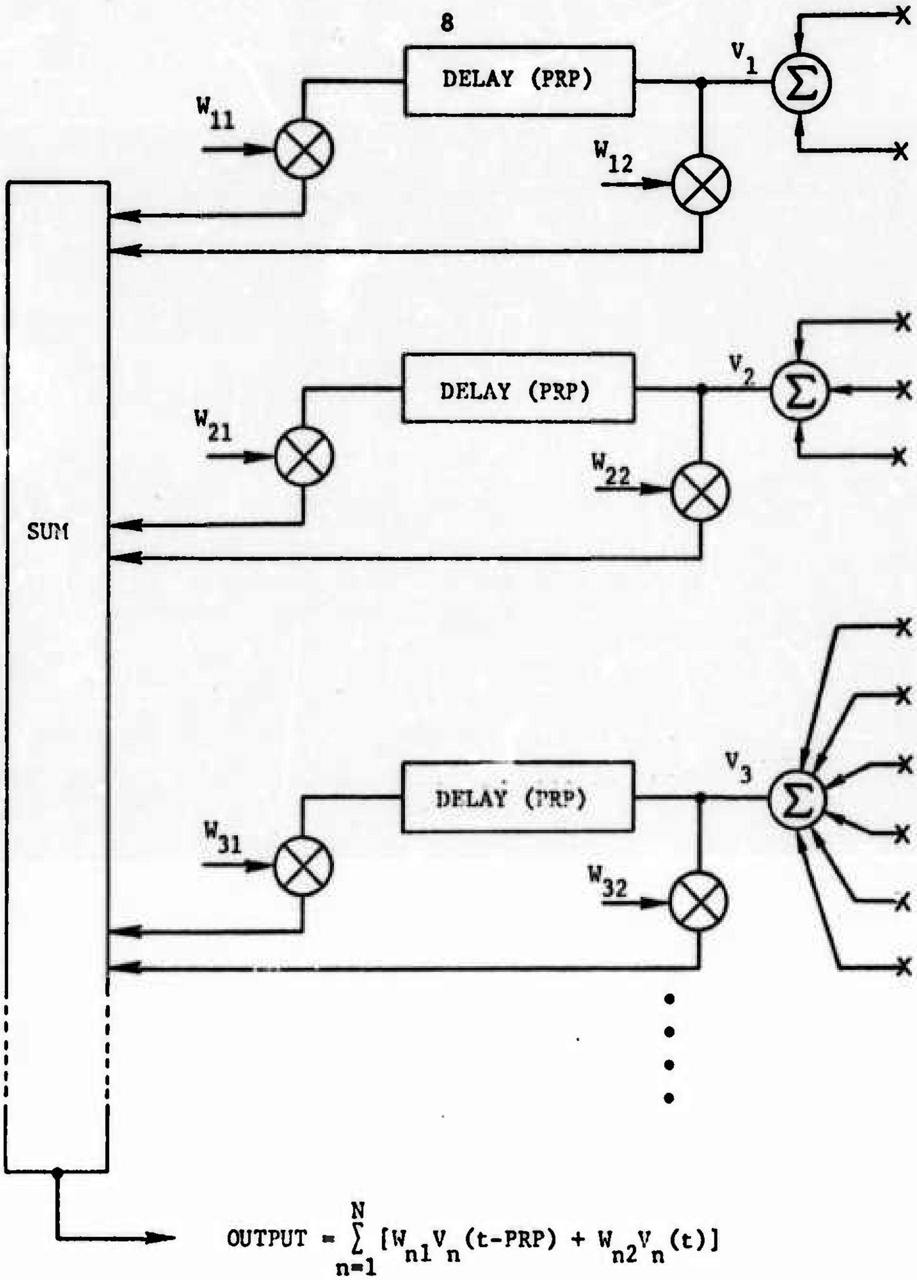


Figure 1. Adaptive AMTI Radar with Subarraying

of all elements in a column into a separate column output. These sub-array outputs, e.g. from linear slotted array columns, then form the basic "horizontal linear array" inputs to the adaptive system.

Even with a single dimension of adaptivity there would typically be a large number of adaptive degrees of freedom. For example, a C-band array 3 ft in length contains roughly 30 elements in the horizontal direction. An X-band array of the same width would contain about 60 elements. In many of the cases investigated, a 32 element horizontal array of half-wavelength spaced elements was considered.

As illustrated in Figure 1, the adaptive system obtains subarray inputs from sets of elements in the horizontal linear array antenna. The subarrays are of arbitrary size, and in several of the cases investigated were unequal in size with smaller subarrays near the edges of the antenna. Two adaptive weights are generated for each subarray output as shown in Figure. 1. The Applebaum type of adaptive loop[5], with steering signals matched in angle and doppler frequency to a target return, can be used to generate the adaptive weights $W_{n1}$ and $W_{n2}$. This space-time adaptive AMTI technique is discussed in more detail in Ref. [6]. Each subarray output is followed by a delay line of one pulse repetition period (PRP) delay, so that two consecutive outputs from each range cell are available for simultaneous processing. One parameter in the analysis is the distance the radar moves between pulses, expressed as a fraction of antenna length ($V_p$(PRP)/L, where $V_p$ is platform speed and L is antenna array length). A second parameter is scan angle, which is measured from the radar platform ground track.

An alternative method of obtaining the adaptive weights is formation of a sample covariance matrix, $\hat{M}$, and computation of the adaptive weights using

$$W = \hat{M}^{-1} S^* \tag{1}$$

As discussed in Refs. [2] and [3], this technique provides rapid convergence to near optimum weights. After sufficient averaging time (in a non-varying clutter environment with fixed scan angle) the Applebaum adaptive loops converge to this same set of weights. With either implementation it is necessary to specify a set of steering signals for each array element on two consecutive pulses. The steering signals used in the following cases were matched in angle to the transmitted beam, i.e., normal to the linear array, and matched in doppler frequency to a target moving radially 1/4 wavelength between pulses. The performance was computed for this same set of target parameters and is expressed as MTI gain(6). The maximum achievable gain in most of the test cases is limited to 80 dB by receiver noise.

The first method of subarraying tested is the formation of equal side-by-side subarrays as in Figure 2a. The steady state (optimum) performance achieved with this technique is shown in Table 2. Three examples are shown for a 16 element array. With a fully adaptive system, i.e., one element per subarray, the adaptive AMTI radar achieves 78.3 dB MTI gain. This is close to the receiver limited performance of 80 dB. When two element subarrays are used, reducing the number of adaptive degrees of freedom

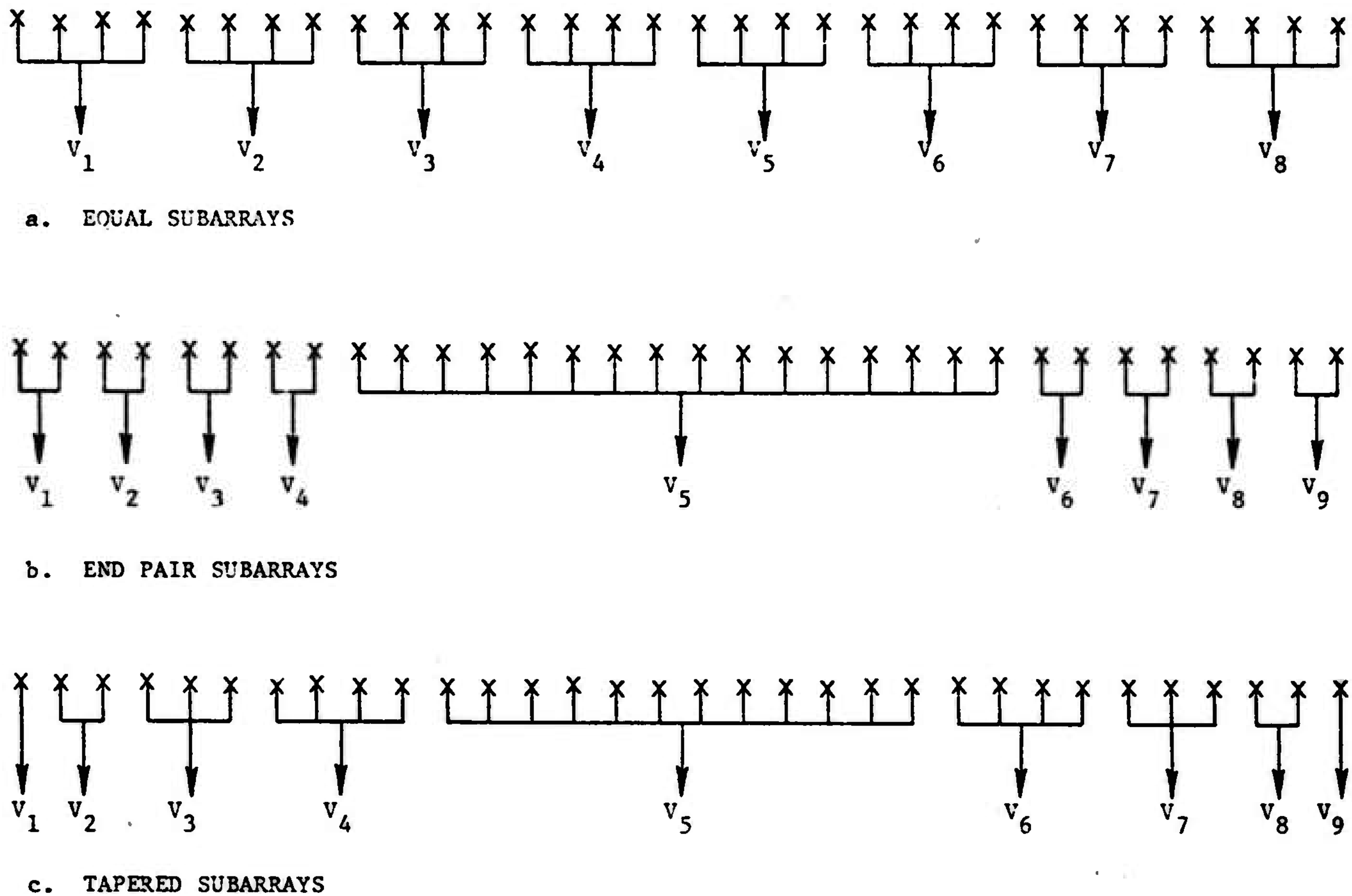


Figure 2. Methods of Forming Subarray Outputs

Table 2. Equal Subarray Performance (Figure 2a)

| Number of Elements | Elements Per Subarray | Number of Subarrays | Scan Angle | Velocity in Antenna Lengths/PRP | MTI Gain (dB) |
|---|---|---|---|---|---|
| 16 | 1 | 16 | 0° | .313 | 78.3 |
| 16 | 2 | 8 | 0° | .313 | 50.9 |
| 16 | 4 | 4 | 0° | .313 | 40.0 |
| 32 | 2 | 16 | 0° | .156 | 64.2 |
| 32 | 4 | 8 | 0° | .156 | 43.0 |
| 32 | 8 | 4 | 0° | .156 | 40.0 |
| 32 | 16 | 2 | 0° | .156 | 37.7 |

from 32 to 16 (two pulse system), the MTI gain is reduced to 50.9 dB. While subarraying in this case results in a large drop in performance, this MTI gain may be adequate for some applications. This is particularly true in the 32 element array examples in Table 2. The use of two element subarray with 32 degrees of freedom provides 64 dB of MTI gain. This is adequate for most AI radar systems and would reduce the system complexity and cost by a significant factor by comparison with a fully adaptive configuration. In general, the performance of an AI radar would be limited by other effects (e.g., transmitter stability, receiver match, receiver noise, clutter internal motion, or number of bits in a digital system) to less than 64 dB MTI gain.

The optimum weights for the 16 subarray, two element per subarray case, are shown in Figure 3. The amplitudes of the weights are the same on both pulses. As shown in Figure 3, the phases differ from pulse to pulse. The

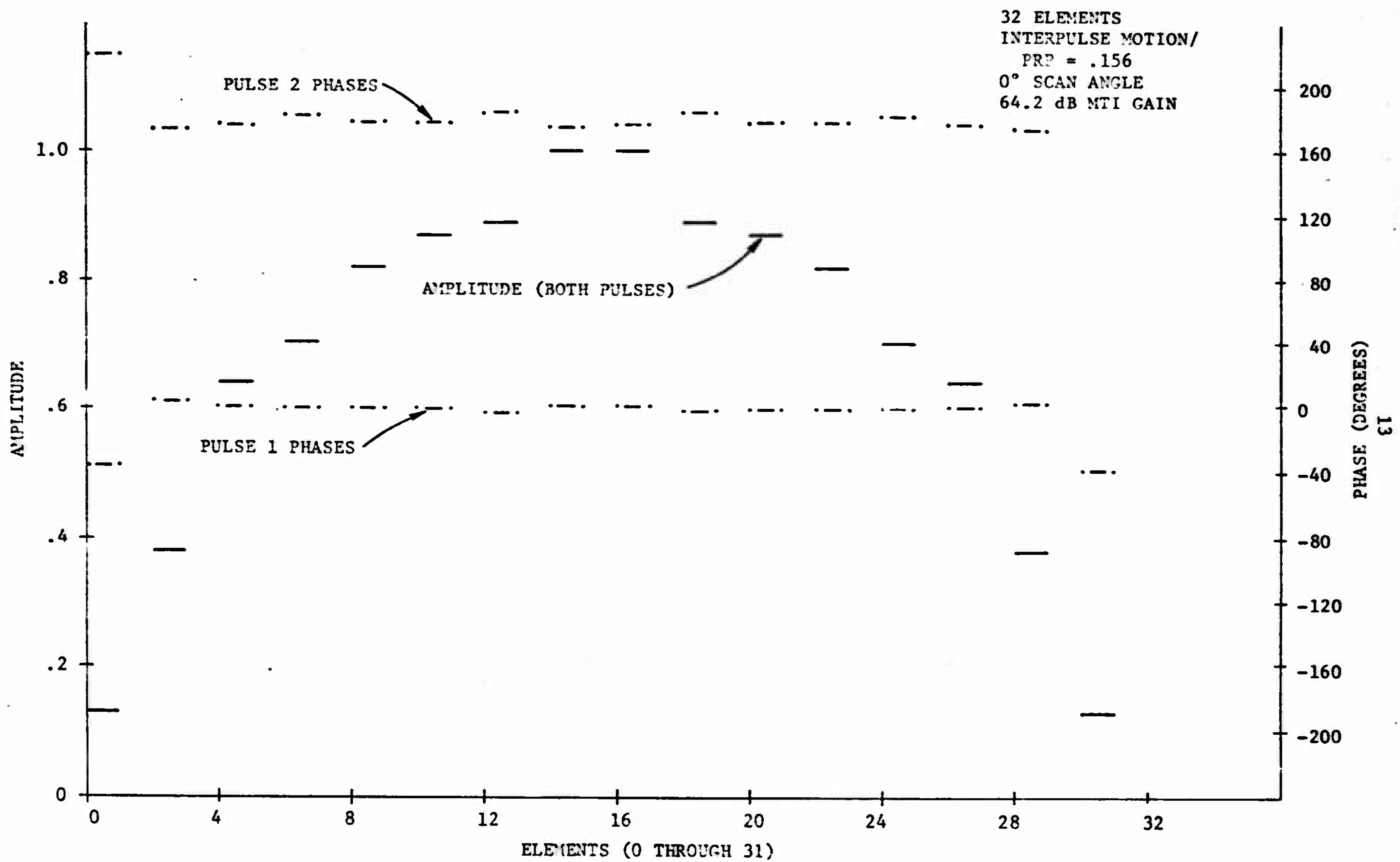


Figure 3. Optimum Weights, Amplitude and Phase - Equal Subarrays (Figure 2a)

symmetry which occurs in this case is due to the 0° scan angle and the assumption of uniformly distributed clutter. The assumed interpulse motion is a representative value for AI radars. For example, at C-band a 32 element array is 3.2 ft wide. The interpulse motion of .156 antenna widths or 1/2 ft corresponds to a velocity of 1000 fps at a 2 kHz pulse repetition frequency.

The results for a variety of unequal subarray cases are shown in Table 3. The first two examples in the table are for end pair (Figure 2b) configurations consisting of eight end pairs and a center segment of 16 elements. The respective subarrays contain 2, 2, 2, 2, 16, 2, 2, 2, and 2 elements. Somewhat better performance was expected with the end pair and tapered configurations than with equal subarrays, since the optimum weights in a fully adaptive system are tapered more severely in amplitude and vary more in phase near the ends of the array. Note that the end pairs configuration with nine subarrays (first row of Table 3) and 18 degrees of freedom provides 59.9 dB MTI gain. The eight equal subarrays (sixth row in Table 2) configuration with 16 degrees of freedom provides only 43 dB for the same parameters, i.e., scan angle and platform velocity. In fact, the nine end pair configuration performs nearly as well as the 16 equal subarray case (row 4 of Table 2).

The optimum weights for the nine subarray case with end pairs are shown in Figure 4. Again, the amplitudes are the same on the two pulses for a given subarray, while the phases are different. These weights correspond to the second row of Table 3.

Table 3. Performance with Unequal Subarrays

| Number of Elements | Elements Per Subarrays | Number of Subarrays | Scan Angle | Velocity in Antenna Lengths/PRP | MTI Gain (dB) |
|---|---|---|---|---|---|
| 32 | 2,2,2,2,16,2 2,2,2 (End Pairs, Fig. 2b) | 9 | 0° | .156 | 59.9 |
| 32 | " | 9 | 0° | .1875 | 58.3 |
| 32 | 1,2,3,4,12,4 3,2,1 (Tapered, Fig. 2c) | 9 | 0° | .0312 | 63.4 |
| 32 | " | 9 | 0° | .0938 | 62.1 |
| 32 | " | 9 | 0° | .1875 | 58.2 |
| 32 | " | 9 | 45° | .0312 | 62.2 |
| 32 | " | 9 | 45° | .0625 | 60.2 |
| 32 | " | 9 | 45° | .0938 | 60.6 |
| 32 | " | 9 | 45° | .1875 | 55.0 |
| 32 | " | 9 | 45° | .25 | 49.8 |
| 32 | " | 9 | 45° | .375 | 42.3 |
| 32 | " | 9 | 90° | .0312 | 79.0 |
| 32 | " | 9 | 90° | .0938 | 78.5 |
| 32 | " | 9 | 90° | .1875 | 46.0 |

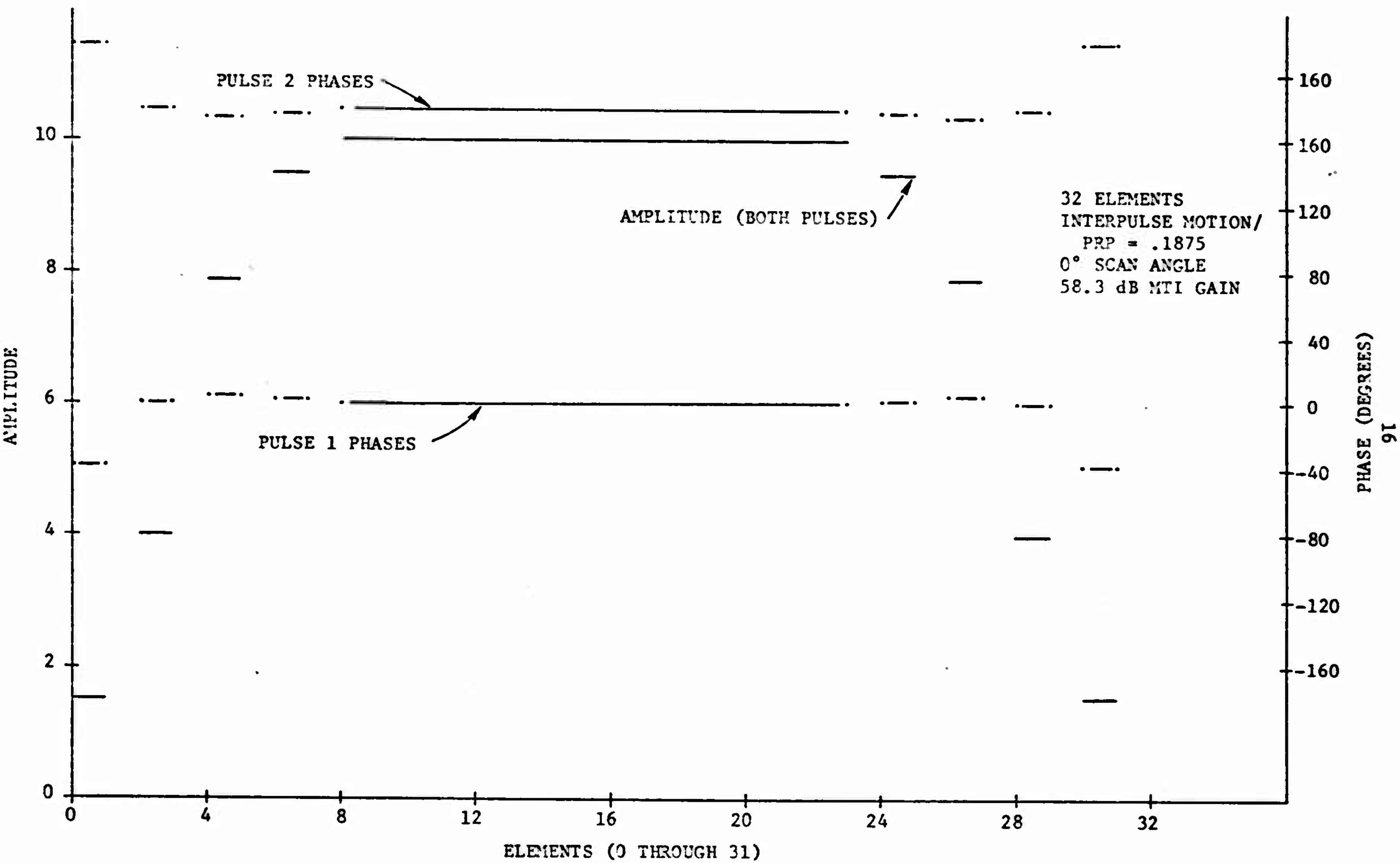


Figure 4. Optimum Weights, Amplitude and Phase - End Pairs (Figure 2b)

The remaining 12 examples in Table 3 show the performance achieved with tapered subarrays (Figure 2c) for a variety of parameter values. Comparison of the second and fifth rows of Table 3 shows that the end pair and tapered subarray configurations perform equally well at 0° scan angle with a platform motion parameter of .1875. Series of examples are shown at 0°, 45° and 90° scan angle as the platform velocity is varied. In general, increasing the radar velocity reduces the adaptive AMTI performance. For a given platform velocity, the performance is better at 0° scan angle than at 45° and better at 45° than at 90°. The figures for $V_p PRP/L = .1875$ are 58.2 dB at 0°, 55 dB at 45°, and 46 dB at 90°. This effect is also observed in a conventional non-adaptive AMTI radar and results from the spreading of the main beam clutter spectrum at angles off the ground track.

Note that excellent performance, close to the 80 dB receiver noise limit, is achieved in the first two examples at 90° scan angle (rows 12 and 13 in Table 3). These cases were selected to correspond to an interpulse motion equal to an integral number of half element spacings. For example, the motion parameter of .0312 antenna lengths is 1/32 of the array length or one element spacing. To compensate for the forward platform motion on both transmit and receive, the illumination function must move backward along the array two element spacings between pulses. This was achieved by setting the three end element weights on the forward end of the array and one end element weight on the aft end equal to zero on the first pulse. On the second pulse, the three end elements on the aft end and one on the forward end are set to zero. This provides exact motion

compensation at the 90° scan angle and an MTI gain close to the 80 dB limit. Since some element weights are zero, maximum antenna gain is not achieved on receive and there is a small loss (1dB) relative to a non-moving radar. In effect, the two element subarrays were switched in and out to accomplish exact motion compensation in this example. Similar performance could be achieved with the end pairs configuration (Figure 2b) at 90° scan angle.

Nearly 80 dB of MTI gain was also obtained in the case of .0938 platform motion and 90° scan angle. In this case, three end subarrays (six end elements) are switched to achieve exactly the required effective antenna phase center displacement. With .1875 platform motion, exact compensation is not possible at 90° scan angle and only 46 dB is achieved.

The optimum receive weights for one tapered subarray example are shown in Figure 5. Again, the weights are tapered to lower amplitudes near the edges of the array and amplitudes are the same on both pulses. This example corresponds to Row 5 of Table 3.

These subarraying results show that, in a typical 32 element wide AI array antenna, adequate AMTI gain can be achieved with roughly nine subarray outputs. This represents a factor of ~3 reduction in number of adaptive degrees of freedom as compared with a fully adaptive system.

To investigate the possibility of further simplification of the system, a different method of generating array outputs was tested. For one representative case of scan angle and platform velocity, the optimum array weights were computed for pulses one and two. Fully adaptive arrays were

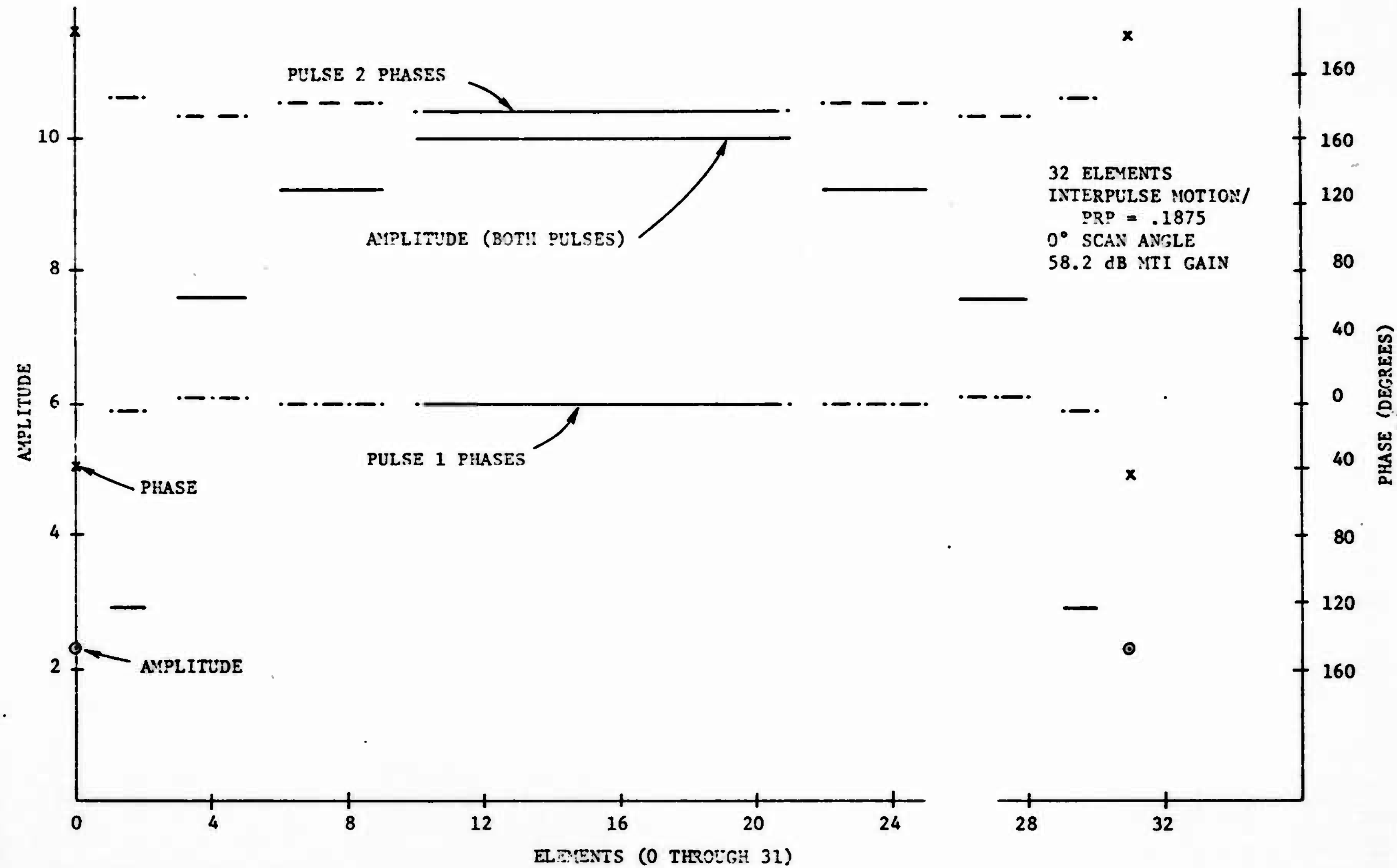


Figure 5. Optimum Weights - Amplitude and Phase - Tapered Subarrays (Figure 2c)

assumed in this weight optimization. Next, it was assumed that these two sets of weights were fixed and the outputs corresponding to these two weight vectors are available from the antenna. For example, fixed RF networks could be used to generate the two antenna outputs which are optimized for the reference case.

These two antenna outputs were then used as inputs to an adaptive AMTI system for other cases, i.e., other scan angles. Results for a six element array are shown in Figure 6. In the lower curve, labeled "two weights", the array illumination functions optimized at 0° scan angle were tested at 10°, 20°, and 45°. Only two adaptively controlled weights were generated in these cases, so there was no possibility of changing the effective array illumination function from pulse to pulse. The MTI gain drops rapidly as the antenna is scanned away from the 0° design angle.

The other two curves of Figure 6 are of more interest. In these cases, four adaptively controlled weights were assumed. The two array outputs are combined on the first pulse with weights $W_{11}$ and $W_{12}$ and on the second pulse with weights $W_{21}$ and $W_{22}$. The system has four degrees of freedom and permits changing the effective illumination function between pulses. With these additional degrees of freedom, the performance is much better. The system optimized for 45° scan angle provides 55-60 dB of MTI gain at both 0° and 90°. Similarly, the system optimized for 0° scan angle yields over 55 dB gain at 10° and 20°.

This technique can be generalized to more degrees of freedom. For example, optimum illumination functions can be generated at two scan angles

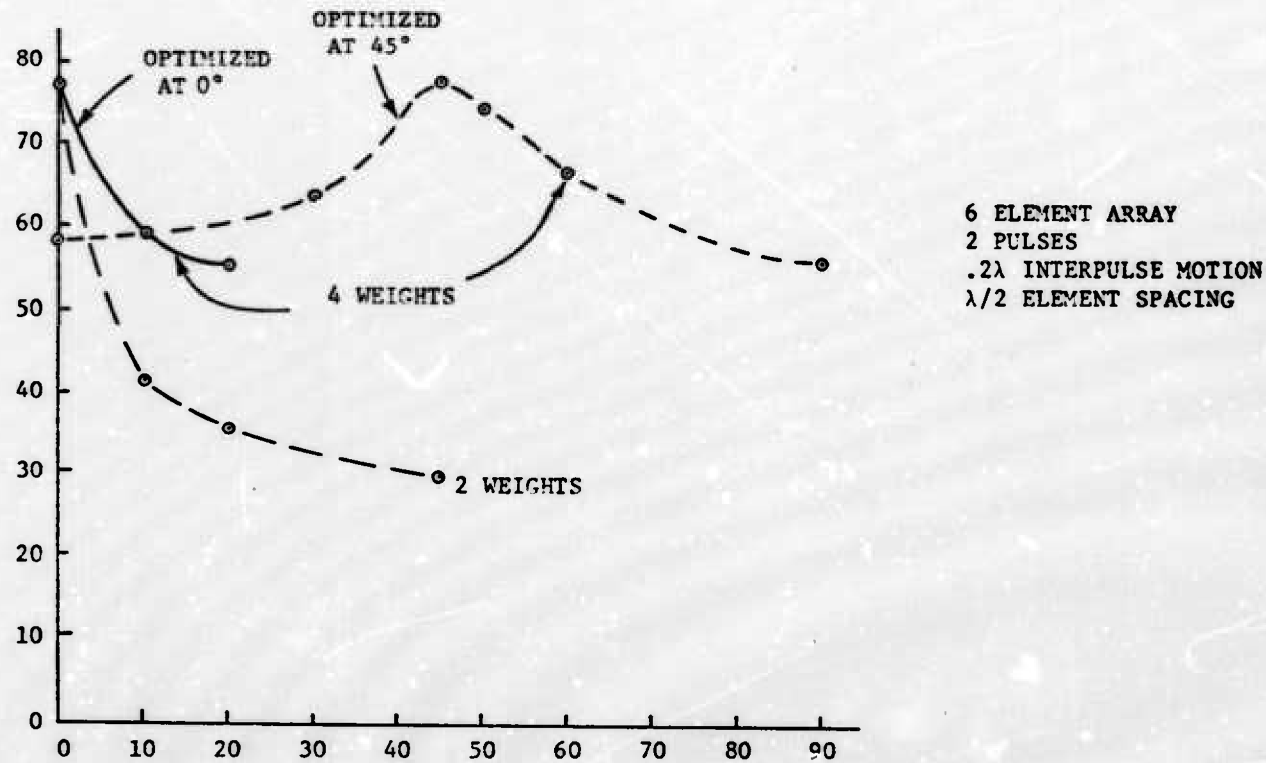


Figure 6. Adaptive AMTI Performance with Two Antenna Outputs

(e.g. -20° and +20°) on two pulses. These four antenna outputs can be used as adaptive system inputs on two pulses, forming a system with eight degrees of freedom.

The methods used in this study for optimizing a set of illumination functions and computing optimum weights to be applied to the corresponding outputs on two or three pulses can be used in designing an adaptive AMTI system. The results obtained with this technique for a simple six element case (Figure 6) and the subarraying results suggest that a considerable simplification of AI adaptive AMTI radars is possible. It appears that fully adaptive control in azimuth will not generally be required to achieve 50-60 dB of MTI gain.

## 4.0 CONCLUSIONS

a. A sample covariance matrix, based on a relatively small number of samples of the noise field, can be used to obtain near-optimum weights in adaptive array systems[2,3]. The performance of this algorithm is approximately 3dB below optimum when K = 2N, where K is the number of samples and N is the number of adaptive degrees of freedom. This technique provides much more rapid convergence than the array of adaptive control loops in many cases of interest. It will be particularly useful in space-time adaptive AMTI radar, where convergence rate is often very slow in adaptive loop systems.

b. The complexity and cost of an adaptive system increase with the number of degrees of freedom. Adaptive AMTI radar systems can be simplified by subarraying at RF and combining the sub-array outputs with adaptively controlled weights (Section 3).

c. The space-time adaptive AMTI technique can be used in systems with curved antennas, e.g., conformal arrays flush-mounted on the aircraft[1].

d. The performance of adaptive AMTI radar is sometimes degraded in non-uniform clutter environments. This degradation can be reduced, and adequate performance obtained in most cases, by basing the adaptive weights on a sample covariance matrix averaged over the entire range search interval[2].

## 5.0 REFERENCES

1. L. E. Brennan and I. P. Bottlik, "Adaptive Radar Techniques," TSC-PD-096-1, January 30, 1973 -- First Quarterly Report on Contract N00019-73-C-0093.

2. L. E. Brennan, J. D. Mallett and I. S. Reed, "Adaptive Radar Techniques," TSC-PD-096-2, April 27, 1973 -- Second Quarterly Report on Contract N00019-73-C-0093.

3. I. S. Reed, J. D. Mallett, and L. E. Brennan, "Adaptive AMTI Radar," TSC-PD-096-2, April 27, 1973 -- Third Quarterly Report on Contract N00019-73-C-0093.

4. I. S. Reed and J. D. Mallett, "Maximum Convergence Rate in Adaptive Arrays," Presented at URSI/GAP Meeting in Boulder, Colo., August 23, 1973.

5. S. P. Applebaum, "Adaptive Arrays," Syracuse University Research Corporation, Report SPL-769, June 1964.

6. "ADAPTAR Space-Time Processing in Airborne Radars," Technology Service Corporation, TSC-PD-061-2, February 24, 1971.